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Thermal Management Strategy of a Small Scale Data Center

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***Abstract*—This paper studied the thermal management strategies for a small-scale data center with a combination of three hot and cold aisle layouts and air inlet and outlet designs. Computational fluid analysis (CFD) was used to predict the flow characteristics in a data center for 12 designs. The CFD simulation results were further used to assess the data center performance and energy consumption metrics, such as rack cooling index (RCI), index of mixing (IOM), beta index (β), and energy utilization index (η_r). The comparison of results for different solutions found that the hot aisle containment layout produced the most favorable cooling outcome. The design insights learned in the study were used to create a design layout with an improved data center thermal performance.**

***Keywords*—data center thermal management; CFD.**

I. Introduction

Data centers are buildings that house computing and networking equipment, power supply and distribution systems, and cooling systems. They play a crucial role as essential infrastructure to provide data transmission, storage, and computation. The exponential growth of demand for computing power driven by artificial intelligence and cloud computing has led to substantial increase in the number and scale of data centers worldwide. The continuous operation of data centers under high load generates a lot of heat, which requires efficient cooling systems to remove heat to prevent servers shutting down or suffering damage. Data centers are one of the most energy-intensive building types, consuming 4.4% of the total U.S. electricity use in 2023 and 6.7% to 12% as projected by 2028 [1]. The average data center cooling system consumes nearly 40% of the total energy usage in data centers [1]. Reducing power consumption in the thermal management of data centers would mitigate operational costs and prolong the lifespan of IT equipment [2].

Air-cooled cooling is the primary method due to its simplicity, cost-effectiveness, and ease of maintenance [3,4]. In raised-floor air-cooled data centers as shown in Fig. 1, chilled air from the computer room air conditioning (CRAC) units is blown into the underfloor plenum, which then enters the room through the perforated floor tiles. After taking away the heat generated by rack servers, the air leaves the room through ceiling plenum and returns to the CRAC to be chilled [5].

In in a basic hot aisle/cold aisle layout, server racks are organized in alternating rows, creating distinct hot and cold aisles. Servers in one row face the servers in the adjacent row, ensuring that the front (cold air intake) side of servers aligns in the cold aisle, while the rear (hot air exhaust) side faces the hot aisle. Cold air bypass, hot air recirculation, and negative pressure close to the air handling unit [3] are major causes of hot spot and local high temperature in a data center. To avoid the mixing of hot air with the cold air, several air separation configurations have been studied, including cold aisle containment, hot aisle containment, additional ceiling vents/ducts, and other combination designs [6-11].

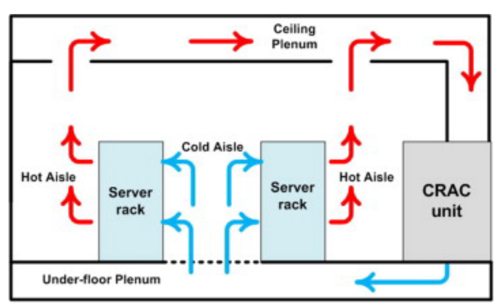


Fig. 1. A basic hot aisle/cold aisle raised-floor data center [5]

While experimental measurements provides validation to the numerical models [7-9], numerical simulation is an indispensable research tool in the filed of data center thermal management [10]. A large number of computational fluid dynamics (CFD) models have been developed to predict thermal performance of data centers during the last ten years using both commercial software packages, such as ANSYS Fluent, STAR-CCM+, 6SigmaRoom, SimScale, FloTHERM, Autodesk CFD, and open-source software OpenFOAM [3]. While CFD models may vary, common details often include CFD simulations with standardization by ASHRAE in terms of allowable temperature, pressure, and recommended heat output from each rack.

This paper presents the CFD simulation results of a small scale data center using a commercial software package, Creo Flow Analysis. Distributions of air temperature and airflow around the racks and thermal performance indices are used to assess and compare the thermal performance of 12 proposed solutions.

II. Methodology

The objective of this research is to find an optimal layout design to improve air distribution and efficiency of cooling for a small scale data center. The distributions of air flow and temperature in the data center was simulated for 12 design alternatives. The overall designs are compared and evaluated with performance indices derived from the simulation results.

A. Physical Models

Fig. 1 shows a data center of two rack rows with conventional uncontained hot aisle/cold aisle configuration. The dimensions of the server room are 7 m x 4 m x 3 m, and each server rack dimensions are 1 m x 1 m x 3 m. There are five racks in each row. The server height emulates that of a large server rack, capable of accommodating up to 42 computer servers. The total power consumption of the racks are 10 kW. Air enters the room from the inlet channels at the floor and leaves the room from the right side circular outlet.

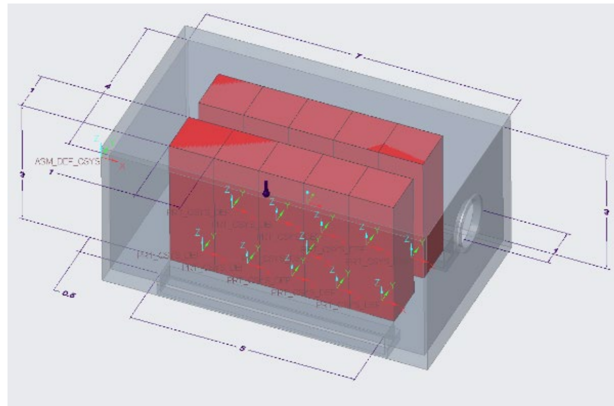


Fig. 2. A server room with conventional hot aisle/cold aisle configuration

The 12 alternative designs shown in Fig. 3 include three layout configurations, namely the Hot Aisle/Cold Aisle configuration, Hot Aisle Containment, and Cold Aisle Containment, and variations of the inlet and outlet designs.

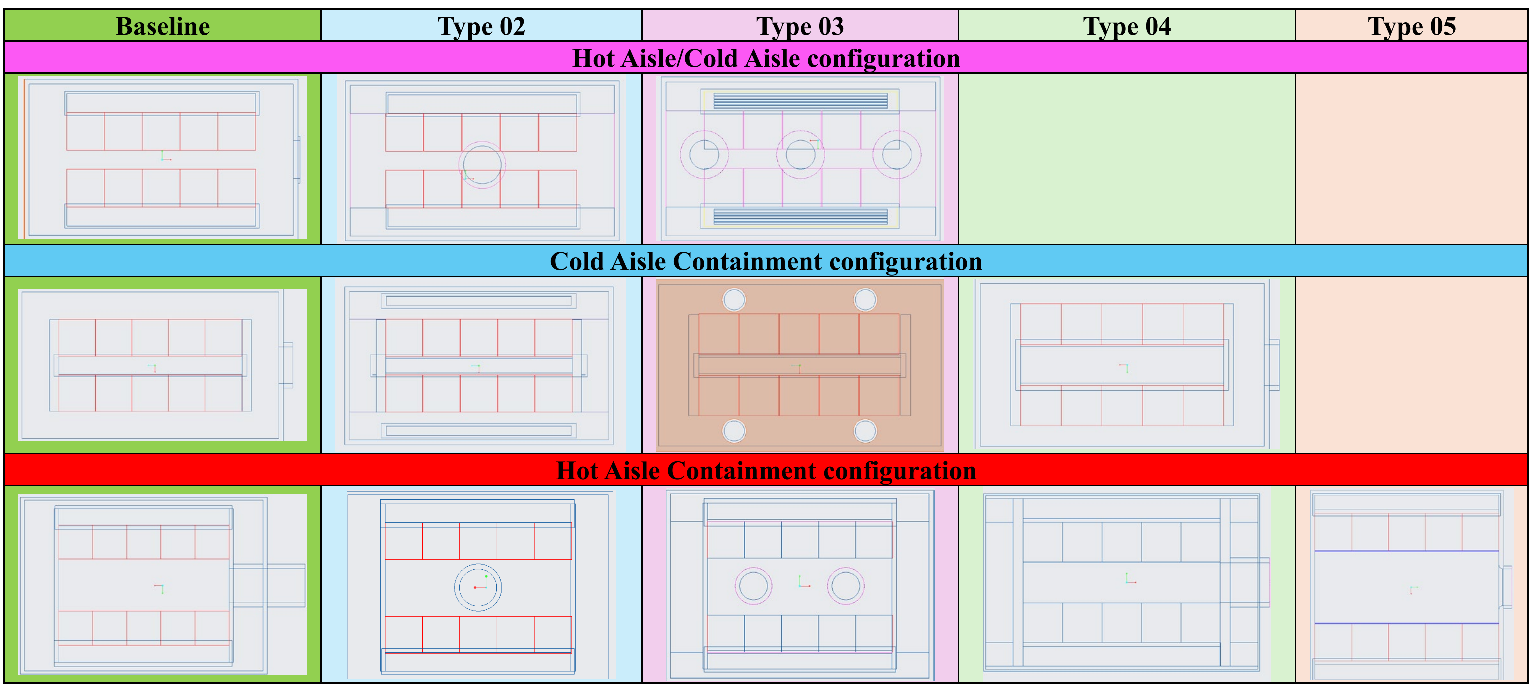


Fig. 3. Alternative designs with three layout configurations with other design combinations

The conventional Hot Aisle/Cold Aisle configuration has two inlet channels, designed to direct cold air into the server racks, each with dimensions of 0.5 m x 5 m. The baseline design has one outlet with a diameter of 1m at the middle of the right wall. Design Type 02 relocates the outlet vent to the top and center of the room. The primary objective of this modification was to achieve a more uniform distribution of hot air within the space. Design Type 03 has three outlets with the diameter of each outlet halved to 0.5 m, resulting in the effective outlet area to ¾ of the baseline design. Additionally, a prorated floor tile was implemented atop the inlet, aimed at directing air at a 45° angle to enhance the cooling efficiency of the server rack.

The Cold Aisle Containment baseline configuration has two walls placed on either side of the server rack to impede the escape of cold air and prevent its mixing with the hot air exiting from the server. This configuration has only one inlet with dimensions of 0.5m x 5m and results in reducing the air volume flow entering into the room to be half. Design Type 02 incorporates alterations in both outlet location and size. It has four rectangular shape outlets with dimensions of 0.25m x 5m placed at the four corners. Design Type 03 has four outlets, each with a diameter of 0.25m, evenly distributed on both sides of the hot air area. The outlet surface area is reduced to ½. Design Type 04 increases the inlet dimensions back to 1m x 5m, the same dimensions used for the Hot Aisle/Cold Aisle models and the hot air containment model.

The Hot Aisle Containment configuration confines the central space between the server rows using two walls on the sides of the server racks to prevent the mixing of hot air with the cold air. The dimensions of the design room is expanded to 7m x 5m x 3m, with a 1m increase in width to facilitate more diverse design variations. Design Type 02 relocates the outlet to the middle top of the room. Design Type 03 changes the number of outlets from 1 to 2, and the size of each outlet was reduced to a diameter of 0.5 m. The total outlet area is reduced to half of the baseline design. The two outlets were evenly distributed across the middle of the room. Design Type 04 was primarily based on the hot aisle containment baseline design, incorporating some modifications in room design. The contour of the inlet was altered to a more curved shape with the aim of enhancing cold air intake. Furthermore, the inside contour of the ceiling was adjusted to expedite the directed flow of cold air into the upper section of the server racks. Design Type 05 represented the final iteration, incorporating the lessons learned from various design features to make a concerted effort to enhance the hot air containment layout. This design was more compact, aiming to fully isolate the cold air stream by minimizing the void areas on both the left and right sides compared to the Type 04 design, resulting in dimensions of (5m x 5m x 3m). The inlet retained the same contour as designed in Type 04, while the top of the room maintained the same inside contour. The decision to omit the top contour was prompted by multiple rendering glitches encountered during mesh generation for the fluid region when the top contour area was included. The concept behind Type 05 was to achieve a more direct airflow into the server rack with the aid of the inlet contour, thereby reducing air mixing by eliminating excess void areas within the room.

B. CFD Model

In this study, Creo Flow Analysis, a commercial CFD package, was used to simulate the turbulent flow in the data center. The standard *k-ε* turbulence model used in this model has been found to be appropriate for large, open space environment as in a data center [8]. To enhance computational and simulation resource efficiency, a porous media setting was uniformly applied to all server racks to simulate the inherent design features without necessitating the detailed modeling of every aspect. Heat dissipation of servers is modeled as a heat source of 10 kW.

The inlet temperature is maintained at 286.15K (13°C) and the inlet velocity of 3 m/s to emulate the typical operational conditions observed in a server room environment specified by ASHRAE 8.0. A pressure outlet boundary condition is used at the outlet.

The Standard Mesh setting was employed across all 12 test cases. A mesh independent study was conducted with the Hot Aisle/Cold Aisle baseline model. The finer mesh setting exhibited significantly longer rendering and running times, in contrast to the standard mesh setting. The results did not demonstrate significant differences with the finer mesh. Therefore, the decision was made to proceed with the use of the standard mesh for all 12 test cases.

C. Performance indices

Several parameters are used to evaluate the thermal performance of a data center. Rack cooling index (*RCI*) is used to measure the extent to which the rack intake temperature lie in the allowable range recommended by ASHRAE [12]. Rack intake temperature at the higher end of the recommended temperature range, RCI_{HI}, is described as follows:

$$RCI_{HI} = \left[1 - \frac{\sum_{x}^{n}(T_x - T_{\max rec})}{(T_{max-all} - T_{\max rec})n}\right] \times 100\% \tag{1}$$

where T_x represented the mean intake temperature of the racks, n represented the number of racks. According to ASHARE, the maximum recommended temperature, $T_{\max rec}$, is 27°C and the maximum allowable temperature, $T_{max-all}$, is 32°C. When $RCI_{HI} \geqslant 100\%$, it indicates that the rack intake temperatures lie within the recommended range. When RCI_{HI} is between 0%-100%, it indicates that the intake temperature was greater than the maximum recommended temperature but still lower than the allowable temperature. When RCI_{HI} value is lower than zero, the temperature of the intake is higher than the maximum allowable temperature, which indicates a lot of hot air mixture at the inlet.

Index of Mixing *IOM* [2] is used to measure the overall performance of the data center with the equation:

$$IOM = \frac{T_{i\,max} - T_{i\,min}}{T_{out} - T_{in}} \tag{2}$$

where $T_{i\,max}$ is the maximum temperature intake of the rack, $T_{i\,min}$ is the minimum temperature intake of the rack, T_{out} is the average temperature at the rack outlet, and T_{in} is the average temperature of the rack inlet. In the case of $IOM \geq 1$, this means there was air mixing, thus a lower value of IOM indicated less air mixing and better performance.

Beta index (β) is an index to quantify the airflow pattern [13]. The equation is defined as :

$$\beta = \frac{T_{in} - T_{ref}}{T_{out} - T_{in}} \tag{3}$$

where T_{in} is the average inlet temperature into the rack, and T_{out} indicated the average outlet temperature out of the rack, T_{ref} is the average outlet temperature from the supplier CRAC. The range of β is $0 < \beta < 1$, where 0 indicates no air recirculation. If β is above 1, it indicates a high value of air recirculation and self-heating.

Energy efficiency η_r [4] is used for calculating the thermal efficiency of airflow in the data center. It can be defined as:

$$\eta_r = \frac{T_{out} - T_{ref}}{\frac{T_{out}+T_{in}}{2} - T_{ref}} \quad (4)$$

where T_{out} is the average air temperature at the outlet of the rack, T_{in} is the average air temperature at the inlet of the rack. T_{ref} is the outlet air temperature from the CRAC to the inlet of the room. The energy efficiency measured the percentage of air mixture between hot and cold air. A larger energy efficiency indicates a better cooling system performance.

III. Results and Discussion

The thermal performance of each design is analyzed using the results of CFD simulation. Flow characteristics and performance indices are compared for design insights and finding optimal design.

A. Flow Characteristics

Flow pattern inside the data center is visualized with air streamlines and temperature distribution is obtained through temperature contours at cross-sections. Fig. 4 shows typical 3D view plot with streamlines and section contour plots for three typical models – Hot Aisle/Cold Aisle Baseline, Cold Containment Type 03 and Hot Containment Type 03. Cold air is observed to enter through the floor inlets, pass through the hot server racks, and then flow out with increased temperature through the outlets. Air circulation, mixing cold air with hot air, and hot spot are observed from these plots. The server layouts, and the size and locations of inlets and outlets significantly affect the flow characteristics and the thermal performance of the data center. Lessons learned from considerations such as outlet location, outlet size, and the impact of contour features on airflow were integrated into a final design – Hot Aisle Containment Type 04.

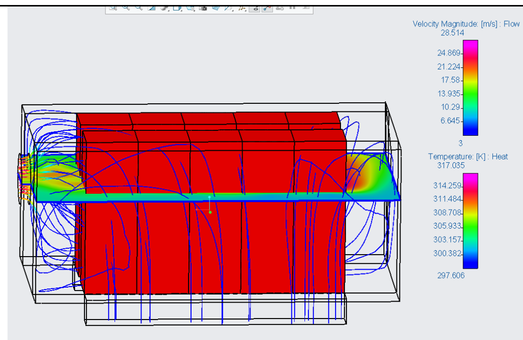
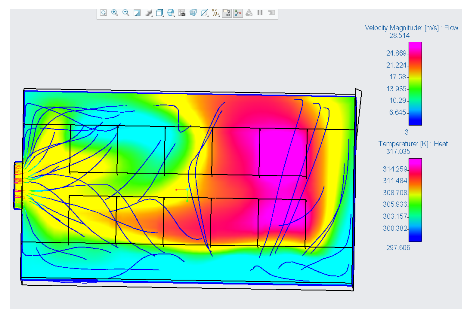
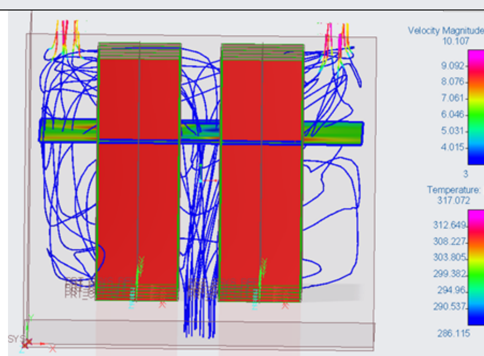
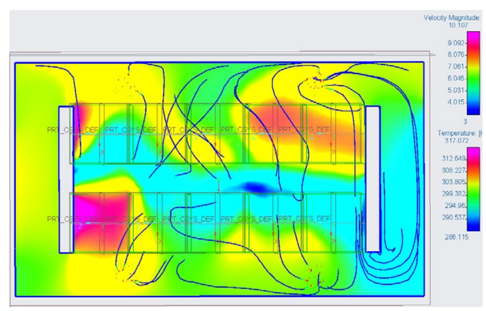
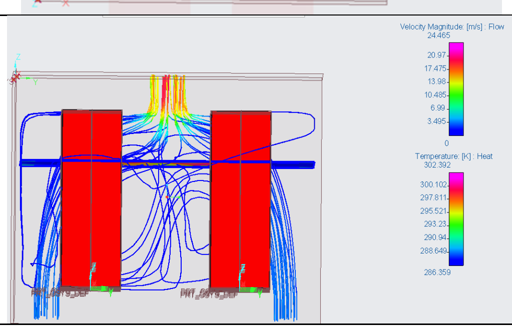
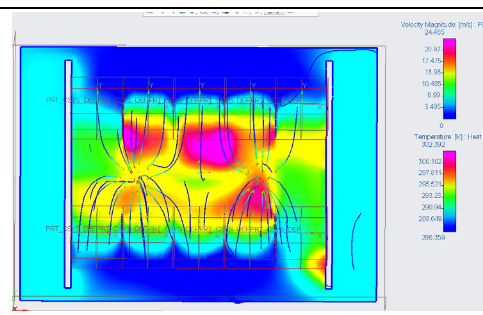
Model	3D View with Section Plot	Section Plot
Hot Aisle/Cold Aisle Baseline		
Cold Containment Type 03		
Hot Containment Type 03		

Fig. 4. 3D Views and section plots for three models

B. *Performance Indices*

Microsoft Excel is used to extract and analyze the CFD simulation data exported from Creo Flow Analysis for the 12 designs. Table 1 lists the thermal performance indices, β, η_r, RCI_{HI}, and *IOM*, ranked by η_r. Figs. 5 and 6 illustrate the performance ranking of the 12 models from best to worst. The nomenclature employed designates HotC as the hot air containment group, ColdC as the cold air containment group, and HotCold as the hot aisle cold aisle group.

TABLE I. TABLE. 1. KEY METRIC CALCULATIONS

Name	beta β	eta η	RCI_Hi	IOM
HotC_T4	0.045	1.913	0.728	0.890
HotC_B	0.097	1.824	0.296	1.965
HotC_T3	0.136	1.761	0.533	1.072
HotCold_T2	0.147	1.744	0.133	7.852
HotC_T2	0.204	1.662	0.450	1.606
HotC_T5	0.225	1.633	0.275	2.733
ColdC_T4	0.230	1.627	0.178	2.403
HotCold_B	0.261	1.586	0.262	3.093
ColdC_T2	0.274	1.569	0.372	3.374
HotCold_T3	0.408	1.421	0.176	8.755
ColdC_B	0.620	1.234	0.344	1.811
ColdC_T3	0.623	1.233	0.516	4.617

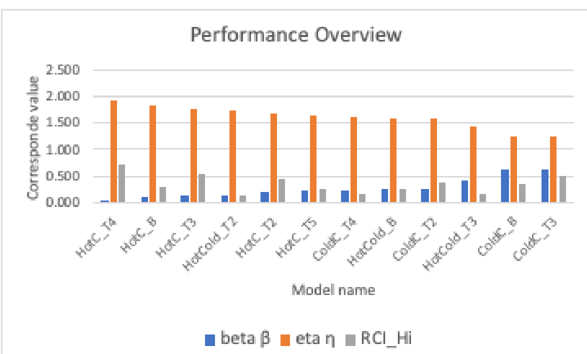


Fig. 5. Performance metric overview

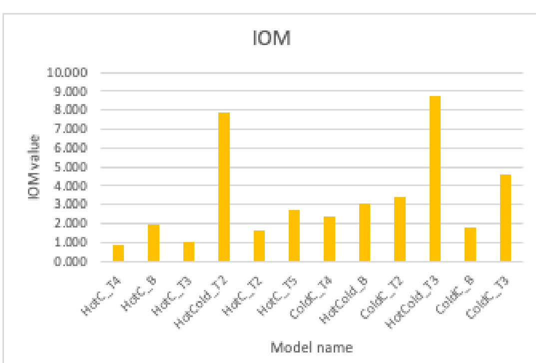


Fig. 6. Index of Mixing (*IOM*) of all models

Hot Aisle Containment layout deigns are found to have the best thermal performance, followed by the Hot Aisle/Cold Aisle layout, then the Cold Aisle Containment layout. Hot Aisle Containment layouts designs have low level of mixing of hot air with the cold air indicated by lower value of Index of Mixing (*IOM*), and lower air circulation indicated by Beta index (β), which leads to higher Rack cooling index (*RCI_{HI}*,) and higher Energy efficiency (η_r). Hot Aisle Containment Type 4 has the best performance among all the 12 designs with (β = 0.045, η_r = 1.913, RCI_{HI} = 0.728, and IOM = 0.89).

While Cold Aisle Containment layout designs have lower level of air mixing compared to Hot Aisle/Cold Aisle layout designs, they have more air circulations identified by the high Beta index. The velocity of air magnitude in Cold Aisle Containment is found lower than other those in the two other layouts as shown in Fig. 4. It indicates that a lower flow rate of cold air passing through the rack servers, resulting in lower thermal performance. This surprising results is related to that the rack fan is not included in the CFD model. When a porous media is used to model the flow through the rack servers, it models the pressure drop across the servers. Without a server fan, cold air bypasses the servers in the Hot Aisle Containment and Hot Aisle/Cold Aisle layouts, but the Cold Aisle Containment restricted cold air pass through the servers, as can be seen from Figs. 4, 7 and 8. This also explains Hot Aisle Containment Type 05 design has low thermal performance.

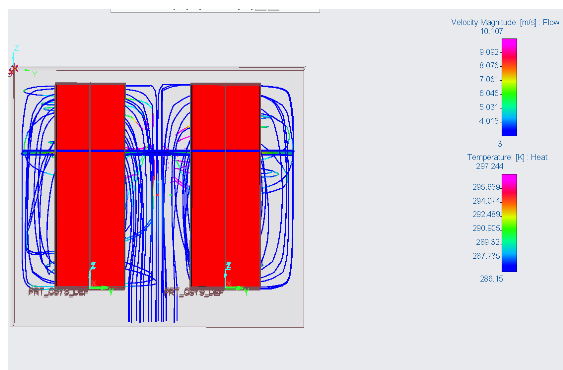


Fig. 7. Air flow trajectory of cold aisle containment Type 04

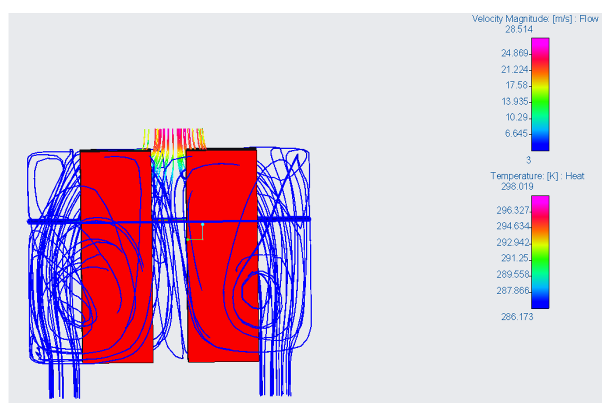


Fig. 8. Air flow trajectory of hot aisle/cold aisle Type 02 model

The effect of location of outlet on the thermal performance is complicated by other factors. While a top centered outlet works better than a side wall outlet for the Hot Aisle/Cold Aisle layouts, it has worse performance for Hot Aisle Containment layouts. Placing outlet above the hot aisle increase air circulation and leads to uneven air flow rate through rack servers.

Reducing the inlet sizes (Baseline, Type 02 and Type 03 of Cold Aisle Containment) and outlet sizes (Hot Aisle/Cold Aisle Type 03, Cold Aisle Containment Type 03, and Hot Aisle Containment Type 03) all lead to lower thermal performance.

CONCLUSIONS AND FUTURE WORK

Numerical investigations of the airflow and thermal performance of a small data center have been conducted for 3 different server rack configurations with the combination of other design considerations, such as inlet size, and outlet size, shape and locations. The results showed that an optimal design is a combination of multiple design parameters.

While the current CFD model provided design insights for data center thermal management, a fan model is required to model the flow through the server rack. In the future, a fan model will be included to appropriately simulate the airflow and thermal performance in a data center.

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